STELLARATORS AS A FAST PATH TO FUSION

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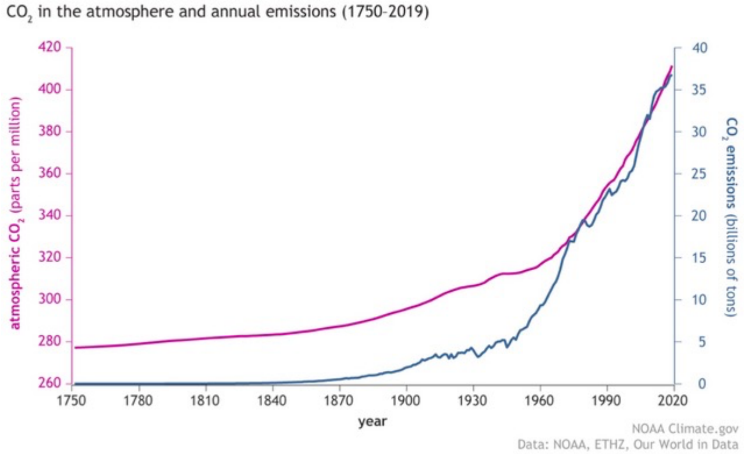
Abstract

The enhancement of the atmospheric concentration of carbon dioxide is doubling every forty years. Options must be developed for energy production that do not drive carbon-dioxide emissions and can be fully deployed within a few doubling times. Unit size and cost of electricity are only relevant in comparison to alternative worldwide energy solutions. Intermittency, site specificity, waste management, and nuclear proliferation make fusion attractive as the basis for a carbon-free energy system compared to the alternatives. Nonetheless, fusion will not be an option for deployment until a power plant has successfully operated. A critical element in a minimal time and risk program to operate a fusion power plant is the use of computational design as opposed to just extrapolation. The importance of minimizing time and risk is so great that ideally more than one concept would be pursued. Unfortunately, only the stellarator has an empirical demonstration of the reliability of computational design through large changes in configuration properties and scale. The cost of computational design is extremely small, even compared to the present scale of the fusion program. Adequate time for the development of ideas that increase attractiveness and reduce risks requires a quick initiation of design studies of fusion power plants, but this is counterbalanced by the natural resistance to change. As will be shown, that sentiment is contrary to both the needs of society and the status of the science; a shift in the priorities of the fusion program to societal needs is required. The construction cost of a power plant may seem great relative to the risk, but a fusion program of tens of billions of dollars a year would be approximately one percent of the annualized financial benefit of success.

1. INTRODUCTION

The situation in which fusion is being developed has undergone two fundamental changes. (a) A general appreciation by the public that a doubling of the enhancement of the abundance of the carbon-dioxide in the atmosphere every forty years cannot be tolerated much longer. (b) The demonstration that computational design of fusion plasmas confined by magnetic fields actually works when the structure of the confining magnetic field is sufficiently dominated by external rather than by currents internal to the plasma. The presently available options for addressing the problem of carbon-dioxide all have issues: intermittency, site specificity, waste management, and nuclear proliferation. In principle, fusion energy is an extremely attractive solution, but a demonstration fusion power plant must be operated before that option can be judged. The argument for minimizing the time and risk of building a fusion power plant is compelling. The importance to world security far outweighs the financial cost.



NOAA Climate.gov
Data: NOAA, ETHZ, Our World in Data

Fig. 1: The rate of CO_2 emissions is doubling approximately every thirty years and the enhancement in the atmospheric concentration above its pre-industrial level is doubling approximately every forty years. This NOAA Climate.gov graph [1] was adapted from the original by Dr. Howard Diamond (NOAA ARL). Atmospheric $CO2$ data from NOAA and ETHZ. $CO2$ emissions data from Our World in Data and the Global Carbon Project.

A picture is worth a thousand words, Figure 1. The rate of carbon-dioxide emissions is doubling approximately every thirty years, and the enhancement of the atmospheric concentration above its pre-industrial level have been doubling approximately every forty years. World security requires something be done before too many doubling times. A solution must be worldwide, or it is no solution. The United States suddenly cutting its carbon-dioxide emissions to zero would only delay the increase in the carbon-dioxide concentration by eight years.

Addressing the carbon-dioxide problem should be a two-step process. First determine the options and then decide on which to deploy. The cost of deployment is far greater that the research required to determine properties of an option. Approximately a thousand power plants would be required for fusion to be a large fraction of the electricity generation capacity of the world, but in principle only one is required to determine the most important features of fusion.

The cost of all options, including doing nothing, is trillions of dollars per year. Replacing the electricity generation capacity of the world and reaching the capacity required within thirty years has a capital cost of ten of trillions of dollars. The cost of each year's emissions can be assessed from the \$50/ton estimate of the social cost of carbon used to set carbon taxes or from the less political number of \$200/ton, which is the estimated cost of direct carbon dioxide removal from the atmosphere [2]. Current emissions are approximately 37×10^9 tons per year, which yields cost estimates of 1.8 to 7.4 trillion dollars a year. Ending the exponential increase in carbon-dioxide emissions and atmospheric concentration is a worldwide security issue and should be treated as such.

Issues of intermittency, site specificity, waste management, and nuclear proliferation for the alternatives make fusion energy very attractive for carbon-free energy production. The importance of minimizing time and risk is so great that multiple fusion concepts could be pursued. Nonetheless, one fusion concept is far better suited for the demonstration of fusion power with minimal time and risk: the stellarator. The fundamental reason is that the magnetic configuration is dominated by the fields produced by external coils rather than by currents in the plasma. This has three implications: (a) Stellarator computational design has an unparalleled reliability [3]. (b) Stellarator plasma maintenance and stability require singularly little active control. (c) Stellarators have an enormous number of degrees of freedom due to their non-axisymmetry, which allows unique features and encourages invention.

The combination of reliable computational design with an enormous number of degrees of freedom makes defining the problems of stellarators subtle. Defined problems can often be solved and turned into advantages. Stellarator design requires largescale computers and an inventive spirit. Stellarator research started seventy years ago in 1951. In that era, the spirit of invention was strong but computers were weak. Now that computers are strong, has the inventive spirit become too weak to achieve the types of things that could be achieved then? It took approximately fifteen years to go from the splitting of uranium to fission powered submarines.

How long would it take to develop fusion if it were considered of comparable importance to security as the development of nuclear fission was in 1939? As was the case then, a rapid development of fusion power would require a carefully organized program that is focused on societal needs and the scientific situation rather than on the sentiments of the research community.

2. STELLARATOR SUITABILITY FOR FUSION

A common sentiment, stated [4] without scientific explanation, is: "The tokamak approach for the plasma core is the most technically advanced and mature confinement concept." Although there are far more tokamak than stellarator experiments, this section will explain why our present understanding of the science implies a stellarator offers a far easier and more certain development path for fusion power on the shortest possible timescale.

2.1. Deuterium-tritium issues

A number of the scientific issues are given in a Nuclear Fusion tokamak-focused review of the deuterium-tritium fusion cycle [5]. This review had a summarizing statement: "A primary conclusion of this paper is that the physics and technology state of the art will not enable DEMO and future power plants to satisfy these principal requirements." The principal requirements were tritium self-sufficiency, tritium for initial start-up, and tritium safety. Stellarators allow limitations stated in [5] to be circumvented:

2.1.1. Tritium breeding ratio (TBR)

Page 7 of the DT fusion cycle review [5] notes: "Physics requirements on the blanket in future fusion systems, such as presence of non-breeding materials for stabilizing shells, penetrations for heating, current drive, and other purposes, are not yet firmly established and can result in a substantial reduction in the achievable TBR."

A fusing stellarator plasma can be maintained with zero current drive or heating power, which are required in tokamaks to retain not only the required plasma current but also the profiles of pressure and current. The robust centering of stellarator plasmas within the plasma chamber and the absence of current driven kinks eliminates the need for stabilizing shells or coils. The absence of disruptions and runaway electrons allows thinner walls. The adequate mitigation of disruptions and runaway electrons for ITER to achieve its mission is extremely challenging [6], but they must be essentially eliminated for a power plant to be feasible [5, 7].

2.1.2. *Burn fraction and fuelling ratio*

Page 13 of the DT fusion cycle review [5] notes: "burn fraction and fueling efficiency represent dominant parameters toward realizing tritium self-sufficiency."

As discussed in [8, 9], the fraction of the tritium that is burned during one pass through a fusion plasma is small but can be controlled since tritium-burn fraction is inversely proportional to $f_t \equiv n_t/(n_t + n_d)$, the fraction of the ion density that is tritium. The fusion power is proportional to $(1 - f_t)f_t$ and hence the $n\tau T$ confinement requirement to maintain a burn are inversely proportional to $(1 - f_t)f_t$. The minimum $n\tau T$ confinement requirement is at $f_t = 1/2$, but at $f_t = 1/4$ the $n\tau T$ requirement is only 4/3 larger. The power output could be controlled by having fuel-injection pellets with differing tritium fractions.

The fueling efficiency might be enhanced in three ways in a stellarator. (a) A stellarator power plant can in principle be designed so the transport is rapid in the inner part of the plasma with the required confinement for fusion given by an outer annulus [10]. The benefit is that the pellet needs to only penetrate the annulus, central aiming is not needed, and the danger of the pellet hitting the opposite wall is greatly reduced, so faster pellets could be used. (b) Stellarators generally do not have strong ELMs, which greatly degrade fueling efficiency. (c) Larger pellets have a smaller edge versus central ablation. Page 30 of [5] said: "We expect shallow penetration of pellets in ITER and a DEMO plasma, even for a pellet with a content of 10% of the plasma content, which is believed to be the limit of density perturbation that can be tolerated without adversely affecting the plasma." Although the Greenwald Limit [11] on the density in tokamaks does not constrain stellarators [11], large oscillations in the density would cause large oscillations in the power output. The optimal size for pellets requires study within the context of the overall power plant.

2.1.3. *Availability*

Page 10 of the DT fusion cycle review [5] notes: "Low availability factors could have tremendous consequences on tritium economy and self-sufficiency: during the reactor downtime...tritium production in blankets is interrupted whilst tritium is continuously lost by radioactive decay."

A low availability can arise either from pulsed operation or from features that give a low reliability, availability, maintainability, or inspectability, which are called RAMI in the engineering literature. The difficulty of achieving efficient maintenance of the net plasma current in a tokamak has led to a consideration of pulse operations, but this issue is not applicable to stellarators. The absence of pulsing and the effects associated with the avoidance and mitigation of disruptions and runaway electrons are of great benefit to the RAMI issues of reliability and availability.

Stellarators have the potential to be designed with coils that allow open access to the plasma chamber [10, 12], which is of central importance to the RAMI issues of maintainability and inspectability.

2.2. Plasma steering, disruptions, and runaway electrons

Before a tokamak can have a successful power plant demonstration the threat of plasma disruptions and runaway electrons must be eliminated [7]. This issue is often posed as an issue of plasma control or steering. Unfortunately [6], "Plasma steering sounds as safe as driving to work but will be shown to more closely resemble driving at high speed through a dense fog on an icy road." Unlike stellarators, tokamaks require active control based on knowledge of the present state of the plasma but have few knobs with which to provide that control and most operate with long time delays. In addition, the diagnostics of the plasma state become far more limited in burning plasmas [13].

Stellarators have no issues that require a major invention, as elimination of disruptions and runaway electrons does in a tokamak [10]. The structure of the magnetic field is dominated by the currents in the external coils, not in the plasma, which imparts a robust stability to stellarator configurations. For example, position control of a tokamak plasma requires the vertical magnetic field evolve as the plasma equilibrium evolves—even feedback stabilization is generally required. A change in the plasma state that is fast compared to the time scale for magnetic fields to penetrate through conducting structures can cause an irretrievable loss in position control. In a stellarator, the time-independent externally-produced magnetic field ensures a plasma can never move far from its designed location in the plasma chamber. In a power plant, the long time-delays of the plasma-control knobs place great importance on passive stability.

Compared to a tokamak, a stellarator has an order of magnitude more distributions of magnetic field that can be produced efficiently by external coils. These fields can be used for design and control. A stellarator has far less need for control but far more knobs than a tokamak for providing that control. A stellarator has unrivaled passive plasma control; no operator intervention is required.

3. ASPECTS OF COMPUTATIONAL DESIGN

3.1. Making fusion energy possible

Until a fusion power plant has operated, the most important question is whether fusion energy is even feasible.

The most important example of computational design removing a block to fusion feasibility is the 1988 demonstration by Nührenberg and Zille [14] that stellarators can have neoclassical transport that is consistent with a power plant. Their work was based on a coordinate system developed by Boozer [15], which generalized a simplified form for the guiding center particle drifts [16]. The benefits of quasi-helical symmetry were seen in HSX, the first stellarator built to study the Nührenberg and Zille type configurations [17, 18].

In non-axisymmetric plasmas, the guiding center drift velocity v_{gc} can carry ripple-trapped particles a distance $v_{gc}\tau_c$ off the constant-pressure surfaces in a collision time τ_c. This gives the ripple-trapped diffusion coefficient $D_{rt} \propto v_{gc}^2\tau_c \propto T_e^{7/2}$, which can overwhelm the gyro-Bohm transport typically seen in tokamaks and stellarators [3, 10], which scales as $T_e^{3/2}$. The ratio of the ripple-trapped to gyro-Bohm diffusion is proportional to the collisional mean-free-path divided the plasma size. This factor is greater than a thousand in a power plant, so ripple-trapped diffusion dominates unless the coefficient multiplying $v_{gc}^2\tau_c$ is extremely small. Ripple-trapped diffusion occurs even in tokamaks because of the toroidal ripple, hence the name, and can be made small in stellarators—even zero on a magnetic surface which defines a confining annulus [10, 19].

The W7-X stellarator was made quasi-isodynamic rather than quasi-symmetric in order to minimize the parallel currents as well as the ripple-trapped diffusion [20]. The expected benefits of this optimization have been seen in the experiments [3, 21– 23].

Judging by the empirical scaling law for stellarators, which as shown in Figure 4 of [3] also works for tokamaks, the micro-turbulent transport is very similar in both and is comparable to the optimal level of transport for a power plant [10]. Nonetheless, optimization methods could be used to modify stellarator transport [24]. This is an area in which far faster computers or deeper physics understanding [25] could make a major contribution.

Axisymmetry eliminates ripple-trapped diffusion. Nonetheless, this comes at the price that the plasma must carry a current that is sufficiently strong to determine properties of the magnetic field, which deprives the plasma of the passive stability and the maintenance properties that are the attraction of stellarators. Unfortunately, theory and computation have not been able to provide solutions to these difficulties of axisymmetry. The efficiency with which a plasma current can be driven has thermodynamic limits [26]. The bootstrap current makes the maintenance of the current easier but also makes current-profile control far more subtle and the delicate stability situation in tokamaks even worse [27]. Major disruptions and runaway electrons, which must be eliminated before power plants become practical, have no clear solution [6]. No solution is known to the Greenwald Density Limit [11] in tokamaks although there is no equivalent problem in stellarators [11].

Divertor designs in stellarators are simplified by the location of the outermost confining magnetic surface being largely determined by currents in external coils rather than a balance between the hoop stress of the plasma current and pressure being balanced by a vertical field and by the absence of the Greenwald Density Limit. The numerical determined island divertor [28] on W7-X has worked as expected [29] and has attractive features. Numerical studies have also been carried out of a non-resonant divertor for stellarators, which unlike the island divertor requires no particular rotational transform at the plasma edge [30–32].

A number of the issues discussed in Section II are additional examples of how stellarator computer-design can address fusion feasibility issues.

3.2. Shortening the time to fusion energy

Computational design can shorten the time to the development of fusion energy.

Tokamaks have advanced by extrapolating from one generation of experiments to another. The abstract of the original paper on the ITER Physics Basis emphasized extrapolation [33]. Skepticism about the reliability of major design changes based on computation is well justified by the dependence of even basic features of a tokamak plasma on its non-linear, self-determined state. The paper that introduced the scientific basis of W7-X emphasized computational optimization of designs [20]. The whole concept of design by computational optimization may seem ethereal to those accustomed to design by empirical extrapolation. Nonetheless, computational design becomes reliable when the structure of the magnetic field is adequately dominated by the magnetic field produced by coils, which can be calculated using the Biot-Savart Law.

Extrapolation has a number of disadvantages in comparison to computational design [10]:

(a) Experiments build in conservatism—even apparently minor changes in design are not possible and therefore remain unstudied. Major changes are risky even when going from one generation of experiments to another

(b) Experiments are built and operated over long periods of time—often a number of decades. A fast-paced program is inconsistent with the need for many generations of experiments.

(c) The cost of computational design is many orders of magnitude smaller than building a major experiment, as well as having a much faster time scale.

(d) Extrapolations are dangerous when changing physics regimes. Examples are (i) plasma control in ignited versus non-ignited plasmas and (ii) the formation of a current of relativistic electrons during a disruption.

3.3. Making fusion more attractive

Contrary to common opinion, once an appropriate stellarator configuration is found, it need not be more sensitive to magnetic field errors than tokamaks. Stellarators do not suffer from the large amplification of the error fields that occurs in tokamaks due to weakly-stable current-driven kinks [34]. Nonetheless, magnetic field errors can cause problems. The issue can be addressed by careful stellarator construction [35] as in W7-X, but this is expensive. Error-field control coils can be used as they are in tokamaks. Condition-number issues of the matrices that relate the control-coil currents to the error-field magnetic distributions limit the number of error fields that can be controlled and careful design [36] should be used to minimize the cost of construction. The same design techniques that give optimal error-field control also allow stellarators to be designed for optimal flexibility in physics studies. The basic principle is that any external magnetic field to which the physics is highly sensitive should be controllable by adjusting the currents in the external coils.

Curl-free magnetic fields can be designed that provide excellent physics properties. Nonetheless, a practical stellarator must have a plasma pressure p or beta, $\beta \equiv 2\mu_0 p/B^2$. The DT fusion power density is approximately proportional to pressure squared [37]; the required plasma pressure is determined by required fusion power density for economic fusion power. The higher the beta, the more efficient is the utilization of the magnetic field. Stellarators can be designed and have beta limits above the 5% usually said to be required for a reactor, but the actual limit seems to be soft [38] and may in practice be far higher. The computational design of stellarators is more reliable when the plasma beta is below all theoretical limits, but this may unnecessarily increase the cost of stellarator power plants. In principle, the required magnetic field can be studied on a demonstration power plant by reducing the magnetic field produced by the coils below the design value.

As discussed, the coils system on a stellarator can be apparently designed for open access. How this should be optimized to simplify maintenance and repair remain to be studied.

4. DISCUSSION

The ITER project was set in motion more than a third of a century ago, in 1985 by Ronald Reagan and Mikhail Gorbachev. At that time, neither the solution [14] to the problem of ripple transport in stellarators (1988) nor the limits [26] on current drive efficiency (1988) and plasma density in tokamaks (1988) were known. The tokamak community was not familiar (1997) with the dangers of runaway electrons [39], nor was the urgency of ending the doubling of carbon-dioxide generally appreciated. Science and society change during a third of a century, and sentiments within the fusion program should change as well.

Seventeen years after the beginning of the fusion program, sentiments changed when tokamaks were shown to have confinement properties far beyond those of any other fusion concept (1968). Nonetheless, the absence of robust stability was concerning since that had been known from early tokamak experiments [40]. It became clear later (1978) that deviations in the profile of the net plasma current can produce disruptions [41], and rapid changes in the magnetic flux associated with the plasma current (1997) can produce destructive beams of relativistic electrons [39]. The Greenwald Density Limit is associated with the current profile [42]. Whatever the cause, this limit complicates divertor design, makes any disruption-free plasma shutdown not only slow, which is required to preserve positional stability, but also difficult especially in a burning plasma [43], and can force tokamak power plants to operate at an extremely high electron, 40 keV, and ion, 60 keV, temperatures [44]. The high temperatures greatly reduce the DT reactivity at a given plasma pressure.

The costs associated with carbon-dioxide emissions, trillions of dollars a year, necessitate a quick determination of options for solutions. For minimization of time and risk, the robustness of the stability and maintenance of the plasma are paramount. As [5, 7] point out, tritium production in a power plant will require the walls to be so thin that mitigation is unlikely to be an adequate response to transient events, such as disruptions; complete avoidance seems to be required. An invention is required for a tokamak to have sufficient passive stability for a power plant. Is the stellarator the required invention that makes the least change in the fundamental concept?

Of all fusion concepts, the stellarator is unique in the extent to which the plasma confinement is externally determined. Stellarators are intrinsically strongly non-axisymmetric, which means careful design is required for adequate confinement. Once fusion power plants exist, major improvements could presumably be made by allowing plasma effects to have a larger role. But having a fusion option is so important to addressing the carbon-dioxide problem that it is prudent to minimize plasma effects to assure success.

The large number of degrees of freedom available for stellarator design and the reliability of computational design create a situation that has no analogue in axisymmetry. For the success and attractiveness of fusion, it is essential that relevant issues be identified in order to circumvent them. Papers, such as [5] on the tritium fuel cycle are critical for inspiring invention. Even stellarator designers tend to come up with power plants that are just bigger versions of existing machines.

The construction of a minimum time and risk stellarator power plant requires approximately five years for innovative computational design. These design studies would cost little compared the present expenditures of many of the national fusion programs—are even within the scope of private funding. Nevertheless, international security is fundamentally a responsibility of government. All of the governments of the world have failed in this responsibility by not establishing the required studies.

The fusion community itself is largely responsible for neither governments nor those who study energy issues to take fusion seriously as a solution. If the community itself does not believe a fusion power plant could be built in fifteen or twenty years with an annual investment that is small compared to a trillion dollars, then it cannot expect others to believe. If fusion cannot be developed quickly, regardless of the funding level, skepticism should be expected on whether fusion can be developed at all.

A recently-completed two-year-long program-planning activity in the United States is an interesting measure of sentiments within that fusion community. The plan was put together by majority votes at a number of large community-wide meetings. The plasma part of the recommended fusion program was heavily tokamak centric but with no emphasis on disruption or runaway issues. The community was asked what a financially unconstrained fusion program would look like; the answer was a slightly augmented version of the present program. The final document [4], which required approval by the U.S. Department of Energy, Fusion Energy Sciences Advisory Committee (FESAC), was published in February 2021. Before approving, the FESAC made one substantial change, on page 31 of the final document. FESAC noted: “The success of ITER and other future high-current tokamaks assumes that the disruption and runaway electron prevention/avoidance/mitigation techniques developed on existing machines translate to practical solutions for those future devices. If such solutions cannot be developed, then” the focus of the program would need to switch to concepts with a lower plasma current.

The needs of society and the status of the science should outweigh community sentiment measured by majority votes. Innovative designs of stellarators for power plants should begin.

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